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Non CO_2 greenhouse gas sources from managed and natural soils - fluxes and mitigation

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1. Introduction

This paper outlines the current knowledge of the processes controlling nitrous oxide (N_2O) and methane (CH_4) fluxes, methods of measurement, mitigation options and models designed to simulate N_2O and CH_4 fluxes. Natural and managed soils are globally important sources and sinks of the main non-CO_2 greenhouse gases (GHG) N_2O and CH_4. Compared to CO_2 their global warming potential over a 100 year period is 298 and 25 times, respectively, larger than that of CO_2.

Keywords:.nitrous oxide, methane, land use change, fertilization, microbial processes
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Soils are the single largest source of N_2O, accounting for over 60% of the global total annual N_2O budget. Tropical forest soils are the largest natural soil source of N_2O (2.11 Tg N_2O y^{-1}) because the wet, warm environment provides optimal conditions for N_2O production. Nitrogen-fertilised agricultural soils, especially in warm wet climates are the largest anthropogenic source of N_2O (4.4 Tg N_2O y^{-1}) (Figure 1).

Global CH_4 production is dominated by emissions from wetlands, ruminants and gas and coal mining. Natural wetlands account for 26% of the global production and rice paddy fields for a further 5%. Soils are also a small, but significant sink for CH_4 (30 Tg y^{-1}). Natural forest soils are believed to be the largest sinks, but their sink strength can change from sink to source, depending on the soil moisture conditions and land management (Figure 1).

2. *Microbial processes leading to N_2O and CH_4 production and consumption*

In soils and waters the microbial processes, 'nitrification', 'denitrification', 'methanogenesis' and 'CH_4 oxidation', are responsible for the soil atmosphere exchange of N_2O and CH_4 everywhere on our planet. In order to model and mitigate N_2O and CH_4 emissions, one needs to understand how these processes operate and how they are influenced by climate, ecosystem type and human intervention (Skiba and Smith 2000) .

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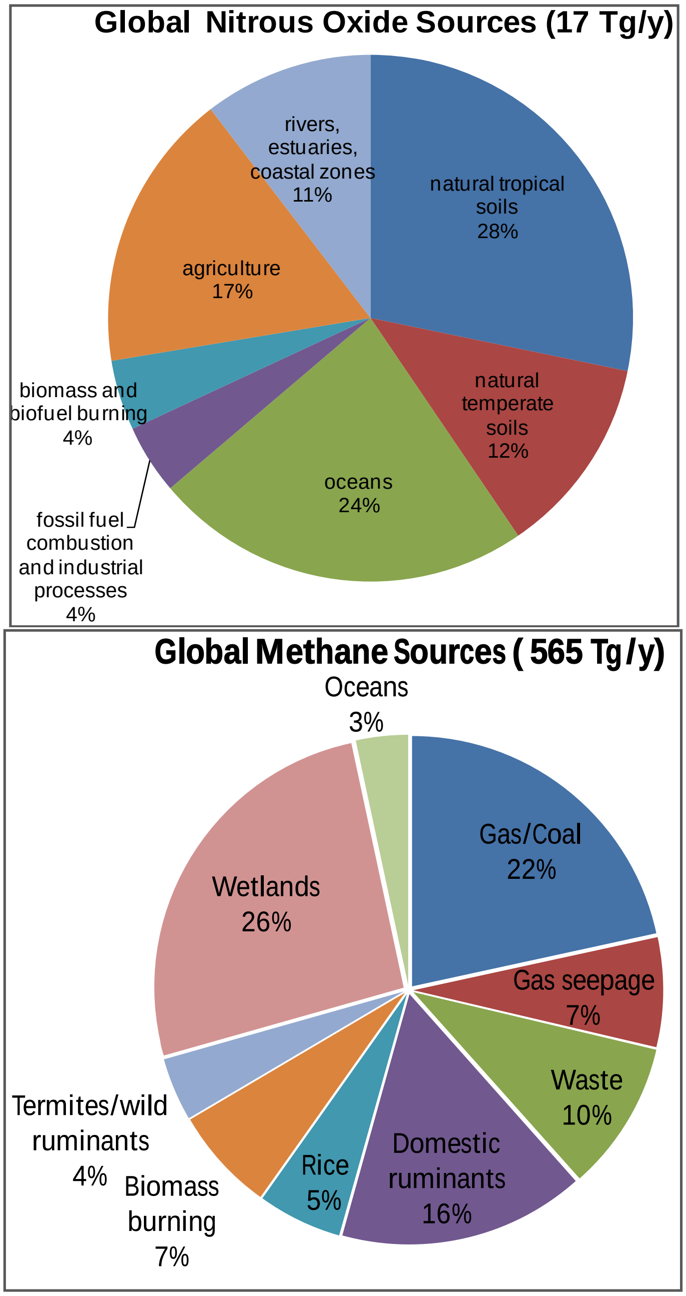

Figure 1: Global N_2O and CH_4 sources (IPCC, 2007; Bousquet et al., 2007).

2.1 Nitrification and denitrification

Nitrification is the oxidation of ammonium to nitrate and requires oxygen and a source of ammonium. This process is a common source of N_2O in the top few mm of the soil and dominates N_2O production when soils are relatively dry. Large rates of N_2O production are associated with denitrification, the reduction of nitrate to N_2O or N_2. This process requires nitrate and simple organic carbon compounds (Bremner, 1997; Davidson, 1991). Complete denitrification to N_2 only occurs in the absence of oxygen, whereas in the presence of small amounts of oxygen, N_2O is the dominant denitrification product. Optimal conditions for denitrification are realised in waterlogged soils or in soils with high oxygen demand. The latter conditions can be achieved by decaying organic matter, root exudates or additions of manure (Wrage et al., 2001).

Nitrification or denitrification can only proceed in the presence of an adequate supply of mineral nitrogen. Most common sources of mineral nitrogen are (i) nitrogen fertilisers, (ii) microbial mineralisation of added organic nitrogen, for example excrete from grazing animals, leaf litter, (iii) mineralisation of stored soil carbon compounds and (iv)atmospheric nitrogen deposition.

The third source of nitrogen is an interesting one. Soils are great sinks for carbon, stored as organic matter. However, when soil is disturbed or drained the organic matter and a lot of the nitrogen locked up in organic soil compounds are released by the process 'mineralisation'. Land use change from forest to arable land is a typical example of soil disturbance and its impact on N_2O production and emission is the least understood.

2.2 Methanogenesis and methane oxidation

Under strictly anaerobic conditions CH_4 is formed during the consumption of simple carbon compounds by very specific groups of microbes. Methanogens are responsible for the large CH_4 emissions observed from rice paddies, peat wetlands, termite mounts and ruminants. In wetlands the key controllers of CH_4 emissions rates are water table height, temperature and plant communities (Laanbroek et al., 2010). A large part of the CH_4 produced in the anaerobic soil layers is oxidised by methanotrophs, which live at the interface of aerobic and anaerobic environments. They use CH_4 as carbon and energy source and require aerobic conditions. Another group of methanotrophs is present in dry soils, where CH_4 production and emission are negligible. This group of methanotrophs used the CH_4 from the atmosphere. They are very sensitive to disturbance, consequently CH_4 oxidation rates are reduced by land use change, drainage, ploughing or nitrogen additions (MacDonald et al., 1997; Zhang et al., 2008, Laanbroek et al., 2010). Undisturbed forests, such as primary tropical forests, with good well-aerated soil structures are the largest sinks for CH_4.

Our understanding of the variables that control N_2O and CH_4 production, emission and uptake is predominately based on measurements of N_2O emissions from nitrogen fertilised soils in temperate, managed ecosystems and of CH_4 emissions from rice paddies and high latitude wetlands. These numerous studies have shown very large spatial and temporal variability, especially for N_2O and CH_4 emissions, hence detailed information of physical and chemical characteristics of the soil, the climate and soil management practices is required to upscale to annual and regional fluxes and identify mitigation options.

3. *Methods to measure soil N_2O and CH_4 fluxes*

Nitrous oxide and CH_4 fluxes can be measured at scales ranging from a few grams of soil to several km. Our global understanding of N_2O and CH_4 fluxes and their control by physical, chemical and microbial processes has largely arisen from static flux chamber measurements (Clayton et al., 1994) . Recent development of high frequency instruments, that detect very small concentration changes, has improved our knowledge of N_2O and CH_4 biosphere atmosphere exchange at the field/landscape scale and at a high temporal resolution (i.e. Fowler et al., 2011). Advancements in satellite technology have made it possible to measure CH_4 and N_2O concentrations from space (i.e. Schneising et al., 2011).

4. *Modelling N_2O and CH_4 fluxes*

Signatories of the Kyoto Protocol are obliged to submit annual accounts of their anthropogenic greenhouse gas emissions, which include N_2O and CH_4, to the UNFCCC. The reporting follows internationally agreed protocols (IPCC, 2006), mostly using simple equations (emission factors), represented by a Tier 1 methodology. The Tier 1 methodology is very simplistic and is designed to calculate emissions based on easily available data. For example N_2O emissions from fertilised grasslands and arable land are assumed to be 1% of the mineral fertiliser N input and CH_4 emissions from rice without organic amendments 20 g m^{-2} (IPCC, 2006).

The Tier 1 emission factor approach assumes a linear relationship between N input and N_2O emission. The emission factor for N additions from (i) mineral fertilisers, (ii) organic amendments and crop residues or (iii) N mineralised from mineral soil as a result of loss of soil carbon, is 1% of N applied, with an uncertainty range of 0.3 to 3%. The reason for the large uncertainty range is that not only N input, but also soil conditions, agronomy and climate are important drivers of N_2O emission. Soil and fertiliser type in particular have been shown to influence N_2O fluxes; but the magnitude of this effect is very varied and cannot be quantified by simple regression equations.

Some countries are currently developing emission factors specific to their growing conditions, management or crop type (Tier 2 methodology). The most complex, but most targeted approach uses process based dynamic models (Tier 3 methodology). Such models use mathematical equations to define the rates of the individual source processes, allowing the model to take a detailed account of site conditions. Climate is a particularly important driver and the models often run on daily or sub daily time steps. In particular for N_2O the denitrification and decomposition model 'DNDC' (Li et al., 1992) has been developed to simulate N_2O emissions. This model also appears to work well for CH_4 emissions from rice paddies (Babu et al., 2009).

5. *Effects of land use change from forests on N_2O and CH_4 fluxes*

Globally deforestation is continuing at a rate of 12.9 million ha^{-1} y^{-1}, primarily as a result of converting forests to agricultural land in South America, Africa and Asia (FAO, 2006). Land use change from forestry invariably requires logging, sometimes tree stump removal, drainage, and ploughing. In the short term these destructive activities will increase microbial decomposition and mineralisation and lead to increased emissions of CO_2, N_2O and CH_4 (Yashiro et al., 2008). It has been estimated that humid tropical primary forests grown on mineral soil lose about 30% of their carbon stock when converted to oil palm plantations or agricultural land (Murty et al., 2002). On peat such conversion results in much larger carbon losses, due to its high organic matter content. Land use change from forestry invariably increases N_2O emissions and reduces CH_4 oxidations rates; and in some cases turns CH_4 oxidation to emissions. The rate of change and length of increased flux rates depends on soil type, drainage, rainfall and land management. However relatively few studies have been undertaken, and there are high levels of uncertainty associated with estimates of greenhouse gas fluxes during land use change.

Interests in growing biofuel as a 'low carbon energy' source have increased conversion of forests and permanent grasslands to growing annual and perennial bioenergy crops across the globe. Calculating the carbon footprint for biofuel production must include soil emissions of N_2O and CH_4 (Crutzen et al. 2008), as these emissions can offset or reduce carbon savings from replacing fossil fuel with renewable bioenergy based fuel (Drewer et al. 2011). Due to lack of sufficient N_2O and CH_4 flux data, carbon footprint analyses of land use change to bioenergy crops are highly uncertain.

6. *A case study: Land use change from primary forest to oil palm*

The Centre for Ecology and Hydrology and the Universiti Malaysia Sabah (UMS), Malaysia participated in the project 'Oxidant and Particle Photochemical Processes above a South-East Asian tropical rain forest' (OP3) funded by the UK Natural Environment Research Council, UK and measured soil N_2O and CH_4 fluxes from primary, secondary forests at Danum Valley and from an oil palm plantation near Lahad Datu, Sabah, Malaysia. The conventional static chamber method was used to measure fluxes (Figure 2). We observed typically large spatial and temporal variability for both gases. Land use change did not significantly influence CH_4 fluxes (Figure 3). Small rates of CH_4 uptake and release were observed at all sites, but they were smaller than those reported for a Chinese tropical primary forest and rubber plantation (Werner et al., 2006). Nitrous oxide fluxes increased with disturbance, and were enormous (6566 µg N_2O-N m^{-2} y^{-1}) near the oil palm tree trunks, where fertiliser was applied into 4 holes around the stem (Figure 3). However, taking into account the much lower emissions from the unfertilised areas of the plantation, suggests an annual emission rate for the entire plantation of 4.4 ± 3.5 kg N_2O-N $ha^{-1}y^{-1}$.

Figure 2: A static chamber measuring N_2O and CH_4 fluxes on an oil palm plantation near Lahad Datu, Borneo. The chamber is sealed for 60 minutes. Air samples were withdrawn at intervals and sent to CEH, Edinburgh for analysis by gas chromatography.

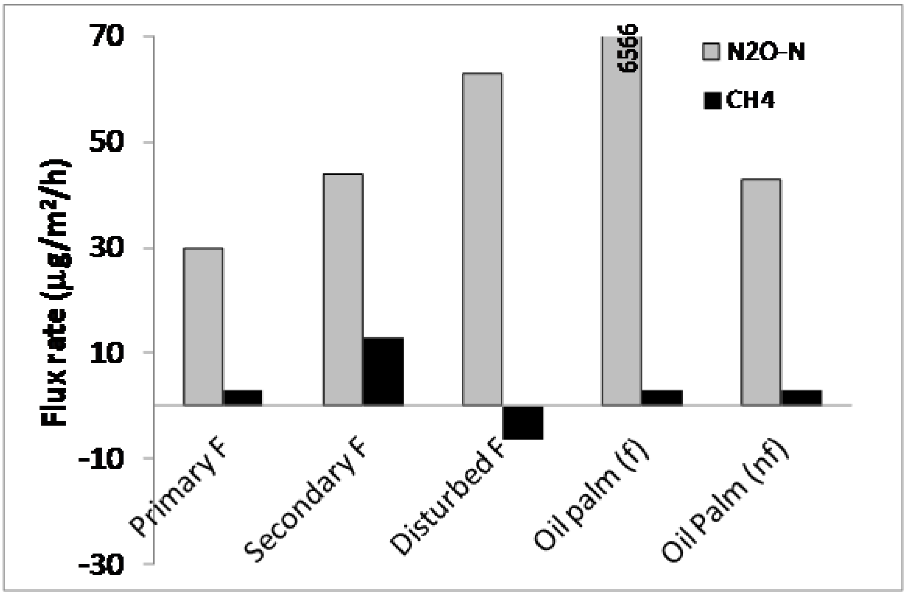

Figure 3: Average N_2O and CH_4 fluxes measured from Forests (Danum Valley) and an oil palm plantation (Lahad Datu) Sabah, Borneo between April and July 2008. Oil palm (f) is the 2 m area where fertiliser was spread; the flux was 6566µ g N_2O-N m^{-2} y^{-1}.Oil palm (nf) is the area on the plantation that was not fertilised.

This emission rate is of the same order of magnitude as emissions reported for an oil palm plantation grown on peat in Sarawak, Malaysia (1.2 kg N_2O-N $ha^{-1}y^{-1}$, Melling et al., 2007). These two examples both show enhanced N_2O emissions when converting forests to oil palm plantations. Their annual flux calculations are based on many assumptions and more research is required to improve the carbon footprint of land use change from forest to oil palm.

7. *Mitigating N_2O and CH_4 emissions*

Reducing N_2O emissions from oil palm plantations is critically important in reducing the carbon footprint of the end product, but because mitigation strategies often require increased nutrient use efficiency, there are both environmental and economic benefits (Rees et al. 2012). Nitrous oxide emissions from managed land can be reduced by

i. Optimising application rates of N, P, K and micro-nutrients for crop type, soil nutrient status, soil type, climate and management. Such management should take full account of any nutrients that are contained in manures or other organic substrates applied to the land. Over- and under-fertilisation, or imbalance in N, P, K micro-nutrients can increase soil N_2O emissions when expressed on a unit product basis (Mosier et al., 1998).
ii. Avoid N fertilisation in high rainfall periods, as this can increase N_2O emissions (Skiba et al., 2012).
iii. Use slow release fertilisers or apply nitrification inhibitors, both reduce N_2O emissions (de Klein and Ledgard, 2005).
iv. Maintain good soil conditions, this includes good soil structure, avoiding compaction and the installation of drainage, where soils retain excessive water (Ball et al., 1999).
v. Use alternatives to synthetic N fertilisers, such as legumes which can be undersown with oil palm, and provide an input of biologically fixed N (Mosier et al., 1998)
vi. Optimise crop management and aim for maximum yield. Thereby less land needs to be cultivated and converted from forests or natural grasslands, avoiding greenhouse gas fluxes as a result of land use change.
vii. Convert grasslands, rather than forest to cropland or oil palm. Land use change from grassland to cropland has a much lower carbon footprint (Germer & Sauerborn, 2007).

Methane emission and oxidation rates tend to be small from managed soils. Land use change often reduces the soil CH_4 sink strength, which however can be improved by maintaining good soil structure, avoid carbon losses and compaction and minimise tillage.

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